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For

**METHOD AND APPARATUS FOR COMPLEX CASCADE SIGMA-DELTA
MODULATION AND SINGLE-SIDEBAND ANALOG-TO-DIGITAL
CONVERSION**

by

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to complex analog-to-digital converters, and more specifically to methods and apparatus for complex sigma-delta modulation.

2. Discussion of the Related Art

Analog-to-digital converters (ADCs) are used to convert analog information to digital information so that signal processing may be accomplished in the digital domain. In particular, sigma-delta ADCs are useful in such applications. Sigma-delta ADCs convert incoming analog signals in a particular frequency span of interest into a high-rate (oversampled), low resolution (one-bit) digital output data stream. The sigma-delta approach to analog-to-digital conversion is well-known for its superior linearity and anti-aliasing performance compared to traditional ADC conversion approaches with lower sampling rates.

In order to maintain the full performance of sigma-delta conversion, it is desirable to implement a “complex” converter, which may be thought of as converting a pair of input signals into streams of digital output values, one such stream representing the “real” or “in-phase” (I) component of the signal, and the other such stream representing the “imaginary” or “quadrature” (Q) component of the signal. It is convenient and common to represent the two output data streams I and Q as a single complex data stream $I+jQ$, where j is a symbol representing the square root of -1.

The advantages of sigma-delta modulators come at some expense. For example, the quantization of the signal produces noise in the output data stream, known as quantization noise. An important job of a sigma-delta converter is to

“shape” this quantization noise out of the frequency range which contains the desired signal, so that subsequent digital filtering operations may recover the desired signal without corruption. In a subsequent stage, this out-of-band quantization noise may be eliminated by means of a filter. In the case of a low-pass sigma-delta modulator, the band of interest spans a frequency range centered around DC, as shown in FIG. 1A, whereas in a bandpass sigma-delta modulator, the center frequency is shifted to a higher frequency, as shown in FIG. 1B.

Two basic possibilities to improve the performance of sigma-delta modulators are the use of a higher-order modulator, or the use of a multi-bit quantizer. These approaches are not necessarily the most effective solutions. The former leads to system instability and latter may cause non-linearity. Cascading of low-order single-bit modulators has been proven to be an efficient way to achieve a higher performance without facing the above-mentioned problems. Cascaded modulators require a digital noise cancellation circuit to remove the quantization noise introduced by the first stages. Consequently, the output quantization noise will be ideally due to the very last stage of the modulator.

As may be seen in references FIGS. 1A and 1B, quantization noise 101, 102+ and 102- and the desired signal 105, 106+ and 106- all remain symmetric with respect to the vertical axes 103, 104 for both the low-pass and bandpass modulators. This way of shaping the quantization noise is wasteful when one side of the spectrum, for example, positive frequencies, provides all the information carried by the signal. For instance, the quantized bandpass signal shown in FIG. 2 exhibits such a property. This property has been the main motivation for using complex sigma-delta modulators

for quadrature bandpass signals. A complex sigma-delta modulator may be implemented using two real modulators with the interconnections between them in such a way that the output complex signal, $y_r + jy_i$, exhibits an asymmetric spectrum for quantization noise.

5 However, it is not possible to use the same principle for baseband signals because the complex signal $I + jQ$ has spectral content at both positive and negative frequencies. For this reason, only real sigma-delta modulators with a symmetric noise shaping characteristic have been used for direct conversion systems, and two real sigma-delta modulators have been required to process the in-phase and quadrature
10 components.

 A single complex modulator is far more efficient in terms of noise shaping than two real modulators operating separately with $x_r = I$ and $x_i = Q$. In other words, for a given number of integrators, a complex sigma-delta modulator provides a better signal-to-noise (SNR) ratio. Alternatively, for a given SNR, a complex modulator
15 requires a smaller number of integrators. This, in turn, translates into a smaller chip area and lower power consumption. The main issue with both cascade and complex modulators is their sensitivity to variation of coefficients. Inaccuracy of the coefficients in a complex modulator degrades the quality of noise shaping and causes image leakage. In a cascade structure, mismatch between the coefficients of the
20 modulator and the coefficients of the digital noise cancellation circuit limits the achievable SNR.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings accompanying and forming part of this specification are included to depict certain aspects of the invention. A clearer conception of the invention, and of the components and operation of systems provided with the invention, will become more readily apparent by referring to the exemplary, and therefore nonlimiting, embodiments illustrated in the drawings, wherein like reference numerals (if they occur in more than one view) designate the same or similar elements. The invention may be better understood by reference to one or more of these drawings in combination with the description presented herein. It should be noted that the features illustrated in the drawings are not necessarily drawn to scale.

FIGS. 1A and 1B are graphs of signal and quantization noise spectra.

FIG. 2 are graphs of quadrature bandpass signals.

FIG. 3A is an example of a complex system having complex input and output signals.

FIG. 3B is an example of a complex integrator.

FIG. 3C is the complex integrator of **FIG. 3B** implemented with interconnected real integrators.

FIG. 4A is a block diagram of a complex second-order sigma-delta modulator.

FIG. 4B is an implementation of the complex second-order sigma-delta modulator of **FIG. 4A**, using real integrators.

FIG. 5 is a 2-2 cascade sigma-delta modulator with real digital noise cancellation.

FIG. 6 is a block diagram of a complex 2-2 cascade sigma-delta modulator with complex digital noise cancellation, in accordance with one aspect of the present invention.

FIG. 7 is an implementation of the complex 2-2 cascade sigma-delta modulator of **FIG. 6**, using real components.

FIGS. 8A and **8B** are block diagrams of radio frequency receivers using complex cascade sigma-delta modulators, in accordance with aspects of the present invention.

FIG. 9 is a block diagram with corresponding graphs of analog-to-digital conversion of a baseband signal using complex sigma-delta modulators and complex filters, in accordance with another aspect of the present invention.

FIG. 10 is a block diagram of a radio frequency receiver using a complex sigma-delta modulator and complex filter at baseband, in accordance with an aspect of the present invention.

DETAILED DESCRIPTION

The invention and the various features and advantageous details thereof are explained more fully with reference to the nonlimiting embodiments that are illustrated in the accompanying drawings and detailed in the following description. It should be understood that the detailed description and the specific examples, while indicating specific embodiments of the invention, are given by way of illustration only and not by way of limitation. Various substitutions, modifications, additions and/or

rearrangements within the spirit and/or scope of the underlying inventive concept will become apparent to those of ordinary skill in the art from this disclosure.

The present invention solves the above-noted discrepancies in prior approached to sigma-delta modulation. One aspect of the invention contemplates a complex cascade sigma-delta modulator comprised of at least two cascaded complex sigma-delta modulators combined with a digital complex noise cancellation circuit. In addition, another aspect of the invention is the use of complex sigma-delta modulators for baseband signals having negligible frequency-spectral content about DC. This results in higher efficiency in analog-to-digital conversion because the required bandwidth of the sigma-delta modulator is halved. In addition, it provides a sigma-delta modulator that enjoys high performance without at the same time suffering inaccuracy due to variation of coefficients. Furthermore, it permits use complex sigma-delta modulators for baseband signals which results in simplified structure, cost and efficiency.

A complex signal $x(t)$ may be represented by its real and imaginary parts as: $x(t) = x_r(t) + jx_i(t)$. Similarly, the impulse response of a complex linear system, $h(t)$, may be represented by its real and imaginary parts: $h(t) = h_r(t) + jh_i(t)$. In the frequency domain, the transfer function of the system becomes $H(z) = H_r(z) + jH_i(z)$. Therefore, the complex system shown in FIG. 3A may be implemented using two real systems. As an example, the complex integrator **301** shown in FIG. 3B may be realized as shown in FIG. 3C, by interconnecting two real integrators **302**, **303**. The complex output signal is similarly given by $y(t) = y_r(t) + jy_i(t)$. The complex integrator **301** has a complex pole at $p = 1 + d + jc$, where d and c are selectable coefficients.

Based on this concept of complex systems, the second-order complex sigma-delta modulator shown schematically in FIG. 4A may be implemented using four real integrators as shown in FIG. 4B.

Referring to FIG. 4A, complex sigma-delta modulator **400** is comprised of two
5 complex integrators **401**, **402**, combined with a complex quantizer **403**. Referring to
FIG. 4B, in a real implementation, and using the principals discussed above with
reference to FIGS. 3B and 3C, complex integrator **401** may be implemented using two
real integrators, **404**, **405**, complex integrator **402** may be implemented using two real
integrators **406**, **407**, and complex quantizer **403** may be implemented using two real
10 quantizers **408**, **409**.

A real fourth-order cascade sigma-delta modulator **500** implemented using two
second-order modulators is shown in FIG. 5. This system uses four real integrators,
501-504, to implement a 2-2 combination. Other combinations of real integrators,
such as 1-1-1 and 2-1 to build a third-order system, or a 2-1-1 combination to build a
15 fourth-order system, are also possible. The extension to even higher order systems is
also possible. The system also employs real quantizers **506**, **507**, and real digital to
analog converters. **508**, **509**. The outputs of the first and second stages are combined
through a real noise cancellation circuit **505** to produce a final output $Y(z)$.

In accordance with one aspect of the present invention, asymmetric noise
20 shaping and cascading are combined in order to achieve a higher performance. The
complex structure creates a single notch for quantization noise and cascading makes
this notch deeper and wider. The general structure of a 2-2 cascade sigma-delta
modulator **600** embodying one aspect of the present invention is shown in block

diagram form in FIG. 6. The complex modulator includes a first-stage 601 cascaded with a second-stage 602. The first-stage 601 includes complex integrators 603 and 604, and quantizer 606, and second-stage 602 includes complex integrators 607, 608 and quantizer 609. The modulator also includes a complex digital noise cancellation
 5 circuit 611.

The output of the first-stage 601, $Y_1(z)$, and the second-stage 602, $Y_4(z)$, in FIG. 6 are described below in equations 1 and 2.

$$Y_2(z) = \frac{z^{-2}X(z) + (1 - p_1z^{-1})(1 - p_2z^{-1})Q_1(z)}{1 + (B_2 - p_1 - p_2)z^{-1} + (B_1 - B_2p_1 + p_1p_2)z^{-2}} \quad (1)$$

$$Y_4(z) = \frac{z^{-2}X(z) + (1 - p_3z^{-1})(1 - p_4z^{-1})Q_2(z)}{1 + (B_4 - p_3 - p_4)z^{-1} + (B_3 - B_4p_3 + p_3p_4)z^{-2}} \quad (2)$$

10 where $Q_1(z)$ and $Q_2(z)$ are the additive quantization noise based on a linear model for the quantizers 606, 609. In the above relations all variables, including the coefficients, are complex. Parameters B_1 , B_2 , B_3 , and B_4 may be set as desired to achieve various results. In general, parameters B_1 , B_2 , B_3 , and B_4 are set so that the denominators of equations 1 and 2 are equal. In this example, parameters B_1 , B_2 , B_3 ,
 15 and B_4 are set as shown in equations 3 and 4.

$$\begin{cases} B_1 = P_1^2 \\ B_2 = p_1 + p_2 \end{cases} \quad (3)$$

$$\begin{cases} B_3 = P_3^2 \\ B_4 = p_3 + p_4 \end{cases} \quad (4)$$

This choice results in:

$$Y_2(z) = z^{-2}X(z) + (1 - p_1z^{-1})(1 - p_2z^{-1})Q_1(z) \quad (5)$$

$$20 \quad Y_4(z) = z^{-2}Q_1(z) + (1 - p_3z^{-1})(1 - p_4z^{-1})Q_2(z) \quad (6)$$

The output complex signal is obtained by combining the complex output signals of each stage 601, 602 using a complex noise cancellation circuit 611 with a complex transfer function $NC(z)$:

$$Y(z) = z^{-2}Y_2(z) - NC(z)Y_4(z) \quad (7)$$

5 Substituting (5) and (6) in (7) leads to:

$$Y(z) = z^{-4}X(z) - (1 - p_1z^{-1})(1 - p_2z^{-1})(1 - p_3z^{-1})(1 - p_4z^{-1})Q_2(z) \quad (8)$$

for:

$$NC(z) = (1 - p_1z^{-1})(1 - p_2z^{-1}) \quad (9)$$

10 Since p_1 and p_2 are both complex, $NC(z)$ is also complex. The choice made in (3) and (4) allows the noise cancellation circuit 611 to be an FIR filter. The noise transfer function of the system is,

$$NTF(z) = (1 - p_1z^{-1})(1 - p_2z^{-1})(1 - p_3z^{-1})(1 - p_4z^{-1}) \quad (10)$$

The four poles of the modulator, p_1 , p_2 , p_3 , and p_4 , may be all at a single frequency or may be distributed in an optimum fashion so as to maximize its SNR.

15 As stated above, $p_1 = 1 + d_1 + jc_1$ and $p_2 = 1 + d_2 + jc_2$,. Thus, the noise cancellation transfer function may be expressed as: $NC(z) = NCr(z) + jNCi(z)$ where,

$$\begin{cases} NCr(z) = 1 + (-2 - d_1 - d_2)z^{-1} + (1 + d_1 + d_2 + d_1d_2 - c_1c_2)z^{-2} \\ NCi(z) = -(c_1 + c_2)z^{-1} + (c_1 + c_2 + c_1d_2 + c_2d_1)z^{-2} \end{cases} \quad (11)$$

20 Therefore, the coefficients c_1 and c_2 used for noise cancellation circuit 611 preferably match with the same coefficients used in the first stage 601 of the modulator 600. Any mismatch between may degrade the performance of the system. The real implementation of the complex cascade modulator in accordance with one exemplary embodiment of the invention is shown in Fig. 7.

Referring to FIG. 7, complex cascaded sigma-delta modulator **600** may be implemented using real modulators and quantizers. For example, the first stage **601** of modulator **600** may include real integrators **701-704** and real quantizers **705, 706**. Similarly, the second stage **602** of modulator **600** may include real integrators **707-710** and real quantizers **711, 712**.

It should be noted that the system shown in FIG. 7 may be implemented in hardware, software and/or firmware, or a combination of hardware, software and firmware, without departing from the scope of the present invention.

Simulation results using Matlab-Simulink have shown that the complex cascaded sigma-delta modulator with complex noise cancellation system, constructed in accordance with FIG. 7 exhibits an excellent noise transfer function (corresponding to an excellent SNR, while at the same time exhibiting excellent immunity to coefficient variation.

Referring to FIGS. 8A and 8B, presented are exemplary embodiments of practical applications of the invention in super-heterodyne receivers. In both FIG. 8A, antenna **801** is coupled to low noise amplifier **802** which produces an amplified radio frequency signal. The output of amplifier **802** is applied to mixers **803** and **804** along with quadrature local oscillator signals, $\text{SIN}\omega_1(t)$ and $\text{COS}\omega_1(t)$. The outputs of mixers **803** and **804** together represent a complex input signal $A + jB$ that is asymmetric relative to DC with the desired signal located at positive frequencies and the image of the desired signal located at negative frequencies (or vice versa).

In FIG. 8A, the complex input signal $A + jB$, is applied to a polyphase filter **806** having an asymmetric frequency response with high attenuation at the image

frequency. The outputs of polyphase filter **806** are applied to complex cascade ADC **807**, which may have the structure and function of complex cascade sigma-delta ADC **600** described above. The digital outputs of complex cascade ADC **807** are then down-converted to baseband by complex mixer **808**, to which are also applied
 5 oscillator signals $\text{SIN}\omega_2(t)$ and $\text{COS}\omega_2(t)$. The outputs of complex mixer **808**, are the demodulated I and Q signals of the received signal, and may then be further processed, for example by DSP **809**.

Alternatively, in FIG. 8B, the outputs of mixers **803** and **804**, $A + jB$, are applied to real band pass filters **810** and **811**, and then to complex cascade ADC **812**.
 10 Once again, complex cascade ADC **812** may have the structure and function of complex cascade sigma-delta ADC **600** described in detail above. The digital outputs of ADC **812** are then down-converted to baseband by complex mixer **813**, to which are also applied oscillator signals $\text{SIN}\omega_2(t)$ and $\text{COS}\omega_2(t)$. The outputs of complex mixer **813**, are the demodulated I and Q signals of the received signal, and may then
 15 be further processed, for example by DSP **809**.

Referring now to FIG. 9, disclosed is another aspect of the present invention in the conversion of baseband signals that have no or insignificant low frequency components. In this application, the input signal $x(t)$ (**900**) has only a real component, and the complex sigma-delta modulator **901** receives only the real signal, and the
 20 imaginary input is grounded. Alternatively, the real signal $x(t)$ may be applied to the imaginary input of sigma-delta modulator **901**. In either case, the center frequency of the sigma-delta modulator **901** is required to be only half of the signal bandwidth.

Complex modulator **901** may be designed so that quantization noise **903** is shaped to include only positive or only negative frequencies.

In one embodiment, sigma-delta modulator **901** may be a complex cascade sigma-delta ADC having a structure and function like that of complex cascade sigma-delta ADC **600**, described above. In another embodiment, sigma-delta modulator **901** may be a complex sigma-delta modulator, such as that shown in FIGS. 4A and 4B, or it may be a complex sigma-delta modulator of conventional design, such as those disclosed in US Patent Nos. 6,225,928 or 6,329,939, the disclosures of each of which are incorporated herein by reference.

The output **905** of the complex sigma-delta modulator **901** is a complex signal, having both real and imaginary components, which are filtered by a digital complex filter **904** which removes out-of-band quantization noise. Filter **904** is a complex filter because the desired frequency response **902** is not symmetrical about DC. Complex filter **904** is of conventional design. Therefore, the quantization noise, **903**, will be present only at positive frequencies in the signal bandwidth. By taking only the real output of filter **904**, the complete signal spectrum at both positive and negative frequencies may be obtained. Mathematically, the output of the complex filter **904** is a complex signal $y(t) = y_r(t) + jy_i(t)$, where $y_r(t)$ and $y_i(t)$ are the real and imaginary parts of the output signal, respectively. Since the signal has no spectral components at negative frequencies, the imaginary part of the signal must be the Hilbert transform of the real part: $y(t) = y_r(t) + jH[y_r(t)]$, where $y_r(t)$ is a real signal having a spectrum that is symmetric about DC.

It should be noted that complex filter 904 may be combined with other digital filters for improved efficiency. Decimation filtering may also be performed at various stages of digital filter 904. In this application, a requirement of digital filter 904 is that it have high attenuation at negative frequencies in order to minimize the error introduced by unfiltered negative frequencies. Thus a sharp filter roll off at DC is preferred. For example, filter 904 may have a cutoff frequency at a positive frequency near DC. In this situation, frequency content between DC and the cutoff frequency may be lost, but this is of no concern if the signal being conditioned has no frequency components close to DC. For example, this embodiment of the invention has applicability to audio signals with no frequency components of interest below 50 Hz. and WCDMA signal with little spectral content below 10 kHz.

Referring now to FIG. 10, presented is an exemplary embodiment of a practical application of the invention in which baseband signals are ADC converted in a zero-IF (homodyne) receiver. In FIG. 10, antenna 1001 is coupled to the input of low noise amplifier 1002 which produces an amplified radio frequency signal that is applied to mixers 1003 and 1004. Also applied to mixers 1003 and 1004 are local oscillator signals $\text{SIN}\omega_{\text{LO}}(t)$ and $\text{COS}\omega_{\text{LO}}(t)$. The outputs of mixers 1003 and 1004 are baseband signals that are applied to low pass filters 1005 and 1006 and then to the ungrounded inputs of complex sigma-delta ADCs 1007 and 1008. Consistent with the operation of ADC 901 discussed above with reference to FIG. 9, ADCs 1007 and 1008 convert only half of the signal bandwidth. The digitized complex outputs of ADCs 1007 and 1008 are applied to complex digital filter 1009 which recovers the entire signal spectrum from the half-spectrum digital outputs of ADCs 1007 and 1008.

The outputs of complex digital filter 1009 are the I and Q signals components of the received signal, and may then be further processed, for example by DSP 1010. It should be noted that complex digital filter 1009 may be a single structure as shown, or filter 1009 may be separate structures, with each structure filtering the complex output of one of the ADC's 1007 and 1008. Still further, the functions of complex digital filter 1009 may be incorporated into the functions of DSP 1010.

The terms a or an, as used herein, are defined as one or more than one. The term plurality, as used herein, is defined as two or more than two. The term coupled, as used herein, is defined as connected, although not necessarily directly, and not necessarily mechanically.

All the disclosed embodiments of the invention disclosed herein can be made and used without undue experimentation in light of the disclosure. It will be manifest that various substitutions, modifications, additions and/or rearrangements of the features of the invention may be made without deviating from the spirit and/or scope of the underlying inventive concept. It is deemed that the spirit and/or scope of the underlying inventive concept as defined by the appended claims and their equivalents cover all such substitutions, modifications, additions and/or rearrangements.